IMAS Pulse Tube Cooler Development and Testing

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ABSTRACT

The Integrated Multispectral Atmospheric Sounder (IMAS) cryocooler has been developed to provide 0.5-watt cooling at 55K in a lightweight compact configuration. The design goal for the cooler was a factor-of-three in size and mass reduction over the AIRS cooler design, with a compressor input power goal of less than 50 W/W — 50% lower than the AIRS cooler at the 0.5-watt cooling capacity. The developed cooler incorporates a vibrationally balanced compressor with heat spreader in the center plate; this further increases the total system efficiency by maintaining a temperature difference of <5°C between the after-cooler and the heat-rejection interface. Two different coldheads have been designed for the IMAS application: an integral-linear option, and a split-coaxial option. The integral-linear option offers efficient performance, and a single warm mechanical/thermal interface. The split-coaxial option offers compactness and some cold interface system advantages. The development of the IMAS cryocooler is presented together with thermal, vibration, and EMI performance data gathered on the cooler both at TRW and at JPL.

INTRODUCTION

The Integrated Multispectral Atmospheric Sounder (IMAS) instrument is an advanced concept instrument being examined by JPL as a second-generation atmospheric sounder for making precision air temperature measurements from space. Key to reducing the mass and power of the IMAS instrument is achieving a new long-life cryocooler with significant mass and size reductions over the AIRS cryocooler[1-5] for the needed 0.5-watts at 55 K focal plane load. This cooling requirement falls midway between the robust cooling capability of existing AIRS-class coolers (1.75 W at 55K) and the capability of miniature long-life coolers, such as the TRW mini pulse tube,[6,7] which has a capacity of approximately 0.5 watt at 75 K. The IMAS cryocooler development effort was carried out by TRW, with JPL as an active integrated product team partner. Figure 1 shows a size comparison between the new IMAS cooler and the larger AIRS redundant cooler system.

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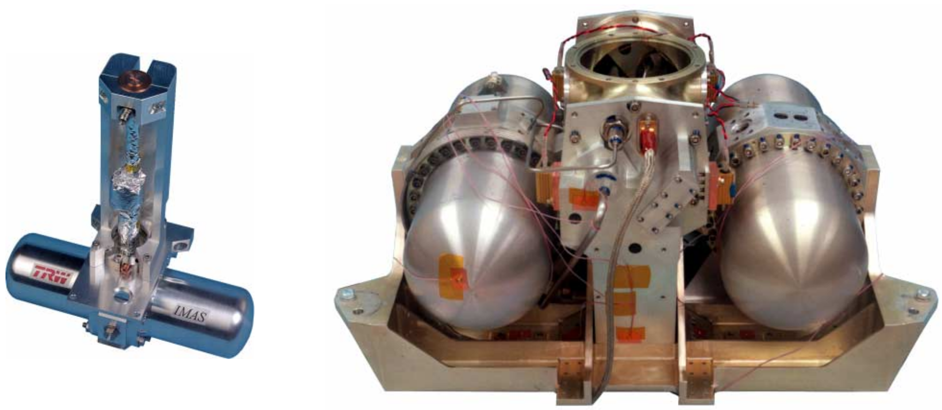


Figure 1. IMAS cryocooler (left) in comparison to the AIRS cooler system (right).

Design Motivation and Requirements

The design load of 0.5 watt at 55 K was derived from detailed calculations of the operational IMAS cryogenic cooling loads from beginning-of-life to end-of-life for the IMAS cryosystem conceptual design shown in Fig. 2. In this system, the compact pulse-tube cryocooler is mounted directly to an instrument-mounted radiator to which ambient heat from the operating cooler is rejected at approximately 270 K. Connection to the 55K focal plane is made using a high-conductance coldlink assembly containing a flexible link to accommodate relative motion created during cooldown and launch. The cold link is supported from the focal plane and provides minimal loads into the pulse tube.

Other fundamental ground rules for the cryocooler system design include:

- Use of a single high-reliability non-redundant cooler to avoid the significant mass and power penalty associated with redundant cryocoolers
- Cooler efficiency goal of 50 W/W with a 0.5 W load at 55 K — 50% better than the excellent AIRS cooler at the same power level (see Fig. 3)
- Total input power goal of 50 watts, and total mass goal of 10 kg, for the mechanical cooler together with its drive electronics
- Compressor and pulse tube reject temperature less than 5°C above thermal interface temperature to maximize operational efficiency.
- Cooler drive frequency fixed at 54 Hz and synchronized to the instrument electronics to eliminate pickup of asynchronous vibration and EMI noise from the cryocooler
- Cooler drive electronics isolated from input power bus; EMI consistent with MIL-STD-461C

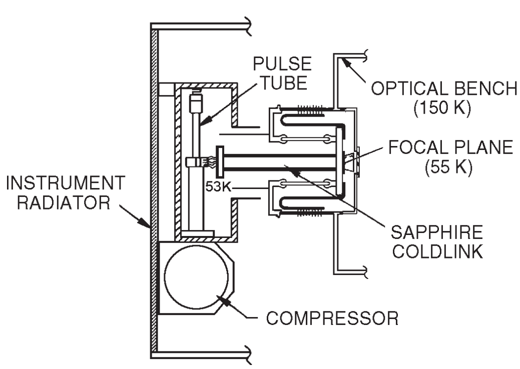


Figure 2. Conceptual design of the IMAS cryosystem.

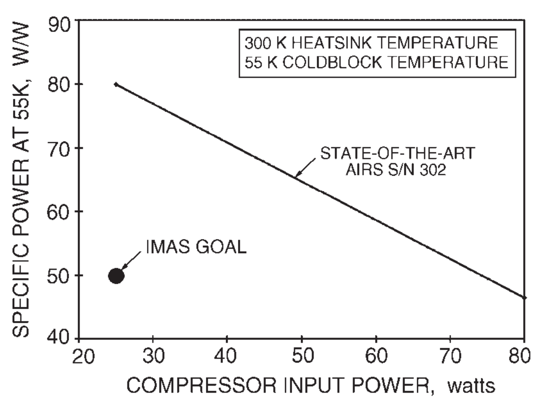


Figure 3. Comparison of IMAS efficiency goal with AIRS efficiency performance.

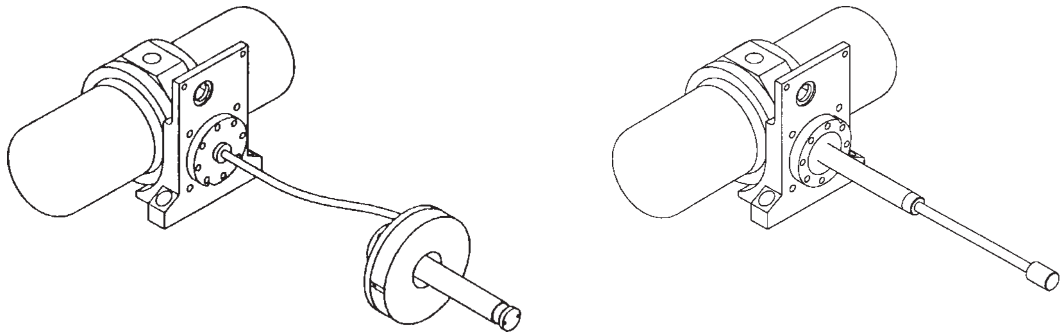
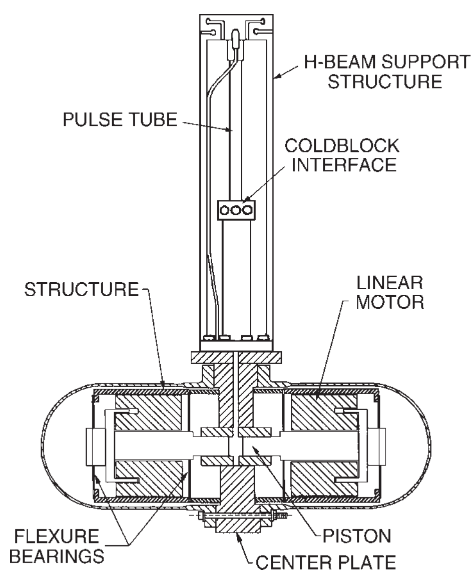


Figure 4. Split coaxial (left) and integral linear (right) pulse tube concepts investigated as part of the IMAS cryocooler development effort.

IMAS COOLER DEVELOPMENT

Because the needed cryocooler performance was outside of the capabilities of existing cryocoolers, a collaborative TRW/JPL teaming approach was established to achieve the necessary cryocooler technology advances. This approach led to the investigation of two pulse tube configurations for the IMAS cooler (see Fig. 4): 1) an integral-linear approach built on the heritage of the highly successful AIRS cooler, and 2) a new split-coaxial design with the promise of reduced mass and improved instrument interfaces. Fundamental to both designs was a new TRW two-piston head-to-head low-vibration compressor.

The high-capacity miniaturized compressor is derived from a joint effort between TRW and Oxford University to develop a next-generation generic flexure bearing compressor of lighter weight, better efficiency, lower EMI, and high-capacity (same class capacity as the AIRS compressor). The majority of the light-weighing potential for a pulse tube cooler lies in the compressor. The IMAS compressor size and mass (as shown in Fig. 5) have been greatly reduced over the current generation AIRS-type compressor by using an entirely new approach to the basic layout of the motor design. The innovative new patented motor and moving coil suspension concept allows great force and stroke in a small package along with lower radiated DC and AC magnetic fields. The compressor motor has a 150 W maximum power capability and has been qualified to a 14.14 Grms launch vibration environment.



Compressor Characteristics

Maximum input power (W)	150
Compressor mass (kg)	2.5
Motor efficiency (%)	82
Swept volume (cc)	4.4 to 6.5
Operating frequency range	50 to 75 Hz
IMAS operating frequency	54 Hz
Maximum pressure (MPa)	3.4
Maximum stroke (mm)	11.6
End Cap diameter (cm)	6.0

Figure 5. Characteristics of the IMAS cooler, shown schematically with integral linear pulse tube.

Figure 6. IMAS cryocooler showing linear pulse tube (left) and heat spreader (right).

The new compressor concept was designed to operate efficiently over a range of swept volumes and operating frequencies by variation of the piston diameter, fill pressure, and moving mass. Two versions have been built to date: the 4.4 cm^3 swept-volume IMAS compressor, shown in Fig. 6, and a larger-piston generic 6.5 cm^3 version that has the same motor design and external dimensions as the IMAS compressor. The moving mass and the smaller piston diameter in the IMAS compressor were selected to provide the needed capacity at the required IMAS operating frequency of 54 Hz, which is established by the need for synchronization with the instrument data-acquisition functions.

In the compressor, the piston shafts are supported fore and aft by flexure springs, which are designed and test-verified for infinite fatigue life. Non-contacting tight gas clearance seals between the piston and the cylinder provide the compression seal in the traditional Oxford-cooler manner. The absence of rubbing, maintained by the flexure bearings, allows multi-year-life capability. To assure helium retention well past the useful life of the cooler, aluminum-jacketed C-rings located between the helium working fluid and ambient provide hermetic metal-to-metal seals.

Piston motion in the new compressor is actuated by moving-coil linear drive motors. The stator motor field is generated by high-strength NdBFe permanent magnets using a cobalt iron return flux path and iron pole pieces. These high-performance materials maximize the field in the motor gap for the least weight, and as with the AIRS motors, provide the potential of $>90\%$ motor efficiency. Internal wiring is stranded, ETFE-insulated or Kapton flexible cable. All wiring exits the bulkhead through ceramic-insulated pins in feedthroughs wired through a pigtail to common D-shell connectors for the power, thermometry, and accelerometers.

To maximize the operational efficiency of the cooler when integrated into the instrument, the cooler has been designed for direct mounting to an instrument radiator or heatpipe interface with less than a 5°C thermal rise above the heatsink temperature. Temperature rise from heatsink to cooler has been a critical issues with previous coolers, and achieving minimal rise is an important design focus for the IMAS cooler. The IMAS cooler uses highly thermally conductive aluminum center plate and end-caps to remove the compressor heat while providing a good thermal expansion match, light weight, and ease of fabrication. Figure 6 shows the closely-coupled integral heatsink/structural mounting interface on the rear side of the IMAS prototype cooler.

The IMAS baseline coldhead is the integral-linear design shown in Fig 6. This design is derived from the successful AIRS coldheads. The linear configuration offers design maturity, higher efficiency, elimination of flow straightener, demonstrated producibility and ease of interface. The H-bar behind the coldhead provides structure rigidity and the heat conduction path from

Figure 7. Prototype coaxial pulse tube coldhead.

the warm end heat exchanger to the center plate of the compressor.

In addition to the linear configuration, a coaxial coldhead, derived from TRW IRAD, was also designed for the IMAS cooling load. The coaxial configuration, shown in Fig. 7, offers an alternative focal plane interface and a potential cooler mass reduction through elimination of the pulse tube structural support.

Either the linear or the coaxial coldhead can be integrated with the IMAS compressor in an integral or in a split configuration. The coaxial split configuration provides an alternate for an advanced focal plane design, especially if the base of the regenerator can be thermally mounted onto a lower-temperature radiator and the focal plane can be mounted directly onto the coldtip. The IMAS coaxial configuration offers a 50% reduction in coldhead mass because it does not require the H-bar. From the system point of view, the cooling load of the coaxial split configuration is also reduced.

The mass of the IMAS coolers in both linear and coaxial configurations is summarized in Table 1.

IMAS Cooler Electronics

Another key issue addressed by the IMAS cooler design is compatibility with the sensitive IR and millimeter-wave detectors and electronics. To reduce noise input to the detector circuits to very low levels, the IMAS cooler baselines the use of TRW's flight qualified, radiation hardened, and high efficiency AIRS/SMTS/TES cooler electronics family. These electronics provide electrical isolation from the spacecraft power bus and use digitally generated piston waveforms to provide precise closed-loop suppression of generated vibration and to provide millikelvin temperature control of the cooler coldfinger so as to achieve the needed fractional millikelvin stability at the focal plane. The key driver on the temperature control is the fluctuating temperature of

Table 1. IMAS cryocooler mass summary.

ITEM	Mass (kg) Integ.-Linear		Mass (kg) Split-Coaxial	
Mechanical Refrigerator Total		3.37		2.98
Compressor	2.500		2.500	
Pulse tube	0.285		0.285	
Pulse Tube H-bar Support	0.385		0	
Reservoir Tank	0.200		0.200	
Cryocooler Electronics (w/ripple suppression)		6.5		6.5
Cables (Electronics to Mech. Cooler)		0.5		0.5
Total Cryocooler Mass		10.37		9.98

ITEM	Design Goal
Output Power	25W to 60W
Input Voltage (Operating)	20-36V
Max Voltage (non operating)	50V
Min. Isolation (Bus to Chassis)	1 μF & 10^6 Ω
Bus Ripple Current Max	1 A_{rms}
Standby Bleeder Power Max	2 W
Electronic Parts Quality	Mil 883B, Grade 2
Radiation Dose and SEU	20 krad
Power Slice Efficiency	78% Min.
Operating Temperature	-45˚C to +50˚C
Launch Vibration	12.9 G_{rms}
Total Mass	6.5 kg
Bus Power	34W to 79W

Figure 8. Packaging concept and design goals for the new IMAS cryocooler drive electronics.

the cryocooler heatsink due to orbital variations in the effective thermal radiation environment, including periodic solar input in some circumstances. From previous measurements of space coolers it is known that every 5°C change in heatsink temperature maps into approximately a 1 K change in coldtip temperature for the same stroke or input power.[8,1]

In addition to the vibration and temperature control functions, the software programmable drive electronics also provide for cooler operational control, and acquisition and transmission of cooler operational data to the IMAS instrument. Relays in the electronics short the compressor motor drive coils during launch to prevent excessive launch-induced piston motion. Design goals for the IMAS electronics are summarized in Fig. 8.

As an augmentation to the AIRS/SMTS/TES cooler electronics, the IMAS cooler development effort is exploring incorporating active ripple current suppression into the cooler electronics. Excessive ripple current fed onto the input power bus is a common problem for all low-frequency linear drive coolers,[9,10] and has been solved to date by the addition of a separate ripple filter in the spacecraft power system. The new ripple-suppression cooler electronics being examined as part of the IMAS cryocooler development effort could result in a savings of several kilograms of total system mass, and greatly improve spacecraft accommodation. Preliminary test data of the new IMAS design indicates the feasibility of ripple current reduction to levels consistent with typical spacecraft power systems. The weight of the IMAS cooler electronics with ripple current suppression is estimated to be around 6.5 kg, as is shown in Table 1. Without the integral ripple filter, AIRS measurements[1] suggest that the projected electrical efficiency is well modeled as P(total input) = P(compressor input)/0.85+5 watts. Because of the addition of the ripple current filter, the IMAS electronics is projected to be P(total input)=P(compressor input)/0.78 + 2 watts.

COOLER PERFORMANCE MEASUREMENTS

As part of the development process, extensive measurements of the performance of the IMAS cooler have been carried out, both at TRW and at JPL. These are summarized in the area of thermal refrigeration performance, vibration performance, and EMI performance.

Thermal Performance

Figure 9 describes the measured refrigeration performance of the IMAS S/N 102 cooler as a function of stroke, input power, coldblock load, and coldblock temperature. In the process of developing the IMAS cooler, several pulse tube coldhead designs have been both analytically and experimentally evaluated. The S/N 102 cooler represents the best performance achieved as of December 1997, prior to delivery of the first IMAS unit to JPL. As noted in Figure 10 the

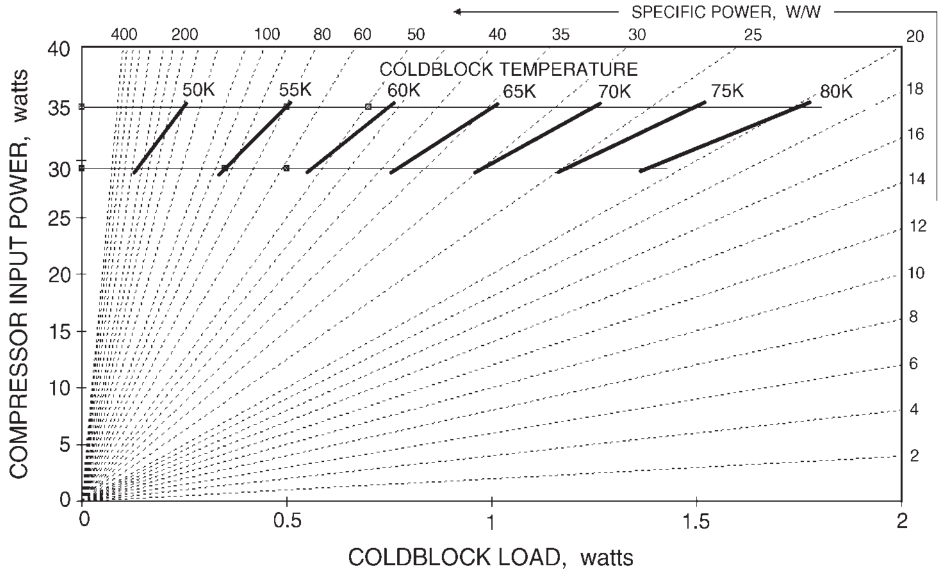


Figure 9. Thermal performance of the S/N 102 IMAS cryocooler as a function of input power, coldblock load, and coldblock temperature.

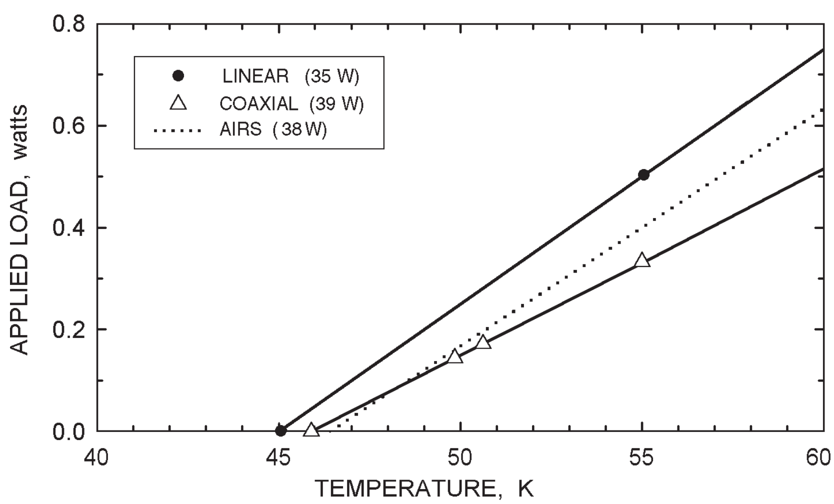


Figure 10. Load lines for the linear-integral and split-coaxial pulse tubes in comparison with the load line for the AIRS cooler at a similar power level and 300 K heatsink temperature.

performance of the IMAS S/N 102 cooler with linear coldhead is better than that of the coaxial coldhead at this point in its development. It also has surpassed the performance of the AIRS cooler[1] at the same 0.5-watt at 55K power level.

Self-Induced Vibration Performance

As part of the exploratory testing effort, the self-induced vibration of the IMAS cooler was tested with both a Texas Instruments Standard Cooler CCA drive electronics (Part No. 2954026-2), which generates a square waveform rather than a sinusoidal waveform, and with a low-harmonic-distortion sinusoidal-waveform laboratory drive electronics. Figure 11 compares the vibration results from the two tests. Although the self-induced vibration levels with the two electronics are quite similar, in the square-waveform case, about 20% of the cooling capacity at 75K was lost for the same input power.

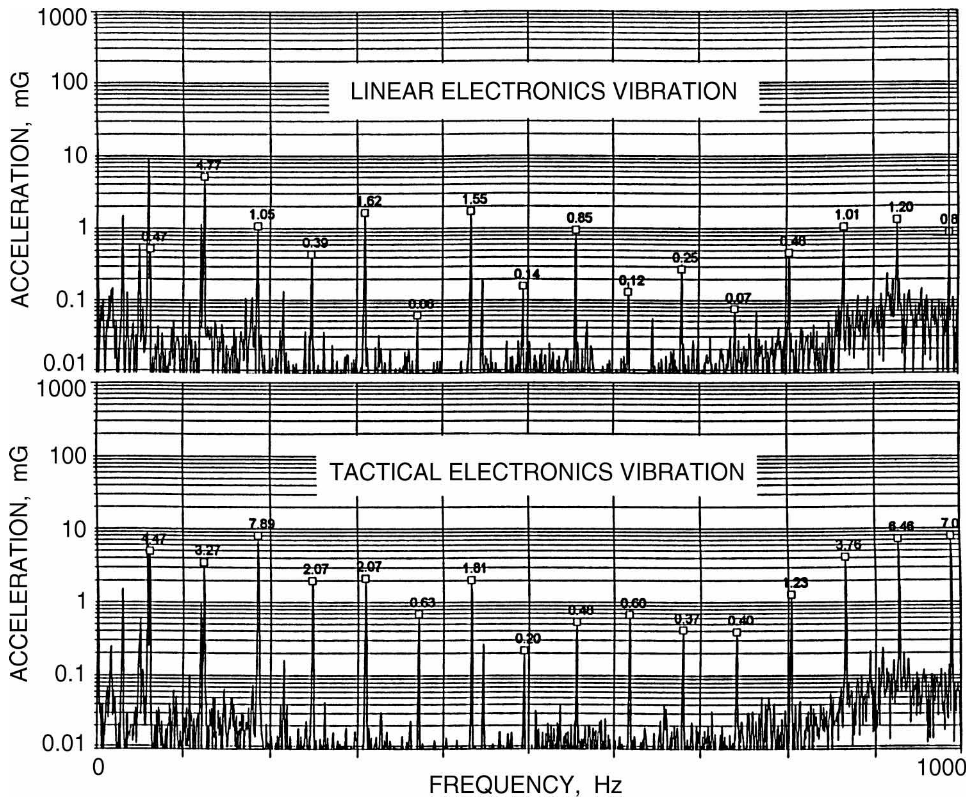


Figure 11. Self induced vibration of the S/N 102 IMAS cryocooler when powered by low-distortion lab electronics (top), and square-wave tactical cooler drive electronics (bottom).

EMI Performance

Another feature of the smaller, lower-power motors in the IMAS cooler is lower levels of AC magnetic fields. Two sets of AC magnetic field measurements were made to quantify the IMAS cryocooler AC magnetic field emissions: 1) at a 7-cm distance, corresponding to the MIL-STD-461C RE01 test specification[9], and 2) at a 1-m distance, corresponding to a MIL-STD-462 RE04 test method. Figure 12 shows the measured RE01 magnetic field performance of the IMAS compressor at 75 watt input power, contrasted with that of the AIRS compressor shown for 105 watts of input power[10]; the data are plotted in decibels above 1 pT. The magnetic field emission levels of the IMAS cooler are quite low compared to other space coolers.[9]

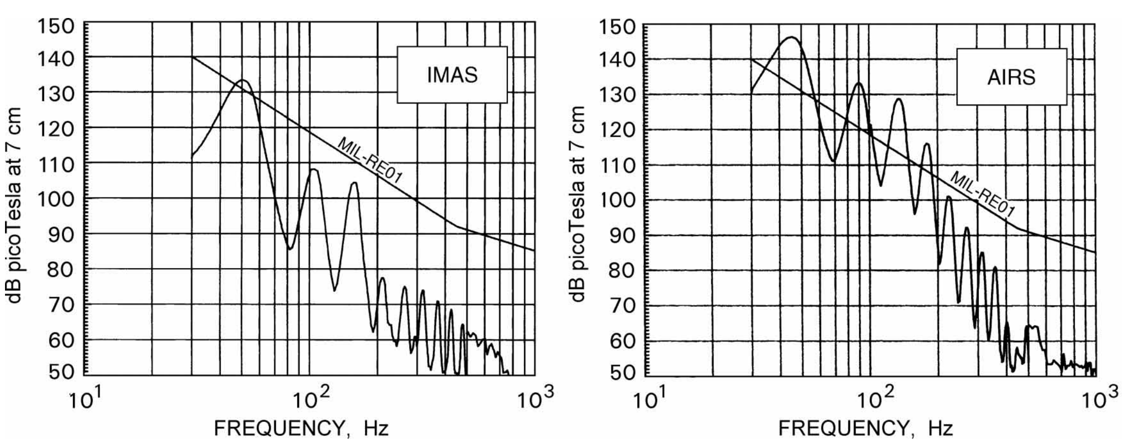


Figure 12. Radiated magnetic fields of the S/N 102 IMAS cryocooler (left) in contrast to those from the larger AIRS cooler (right).

SUMMARY AND CONCLUSIONS

The IMAS TechDemo cryocooler development has been carried out in close collaboration with the IMAS instrument development so as to maximize the performance of the overall instrument. The cooler development is a collaborative effort involving development activities at TRW, and cryocooler characterization testing at JPL. The state-of-the-art pulse tube cooler has demonstrated excellent thermal performance, light weight, low self-induced vibration and low magnetic field emission. Results have been presented detailing the overall cryocooler thermal performance achieved, the cooler's vibration and EMI attributes, and its mass properties.

ACKNOWLEDGMENT

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